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Hurricane Ivan, a category 4 storm, passed directly over six wave-tide gauges deployed by the Naval Research Laboratory on the outer continental shelf in the northeastern Gulf of Mexico. Waves were observed with significant wave heights reaching 17.9 meters and maximum crest-to-trough individual wave heights of 27.7 meters (91 feet). Analysis suggests that significant wave heights likely surpassed 21 meters (69 feet) and that maximum crest-to-trough individual wave heights exceeded 40 meters (132 feet) near the eyewall.

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Extreme Waves Under Hurricane Ivan

David W. Wang,* Douglas A. Mitchell, William J. Teague, Ewa Jarosz, Mark S. Hulbert

On 15 September 2004, the center of Hurricane Ivan (Fig. 1A and fig. S1) passed directly over six wave-tide gauges deployed by the Naval Research Laboratory (NRL), at depths of 60 and 90 m, on the outer continental shelf in the northeastern Gulf of Mexico, allowing us to measure the extreme waves directly under a category 4 hurricane (*1*). We calculated significant wave height (H_s) and maximum individual wave height (H_{max}), two parameters commonly used to characterize wave fields (*2*).

During Ivan's approach, H_s and H_{max} rapidly increased and reached peak values when the radial distance between the eye's center and the moorings was ~75 km (Fig. 1B). H_s reached maximum values of 17.9, 16.1, and 17.1 m at moorings 3, 4, and 5, respectively. These H_s values were larger than those measured the same day by National Data Buoy Center (NDBC) buoy 42040 (Fig. 1A), which recorded the largest H_s (15.96 m) ever reported by NDBC. The largest H_{max} reached 27.7 m (91 ft) at mooring 3; out of 146 waves measured at moorings 3, 4, and 5, there were 24 individual waves with heights greater than 15 m (50 ft) (*1*).

The measured values of H_s and H_{max} depict the radial variability of the hurricane wave field in the range $1 \le r/R \le 8$ (Fig. 1C), where r is the radial distance from the moorings to the eye's center and R is the radius of maximum winds (40 km) (*3*). H_s increased rapidly as the normalized radial distance approached 1 (Fig. 1, B and C) and can be approximated by an exponential curve of the form, $H_s = a(r/R)^b \exp[-(r/R)^c]$, where a = 56.61 m, b = –0.96, and c = –0.94 (Eq. 1). This compares well with a numerical model (*4*), provided the model's H_s is set to 21 m at $r/R = 1$ (Fig. 1C). Past observations of H_{max} during hurricane-generated seas suggest that H_{max} can reach $1.9H_s$ (*5*), which is consistent with the upper limit of our measurements (Fig. 1B).

The wave-sampling strategy (*1*) employed captured a small segment of the wave field, suggesting our measurements likely missed the largest waves near the storm's eyewall. The largest measured H_s reached 17.9 m at a radial distance of 73 km, about 30 km from the strongest winds. Furthermore, our measurements, from the forward face of Ivan, are likely ~85% of the maximum H_s typically found in the right quadrant (*4*, *6*). These factors strongly suggest the wave field associated with Ivan should generate maximum H_s values greater than 21 m and H_{max} values greater than 40 m at $r/R = 1$.

The values of H_s measured here, possibly reduced by shoaling, are larger than those predicted by several parametric wave models developed for deep water conditions. Young (*6*) proposed a semi-empirical model based on R, maximum wind speed (U_{max}), and hurricane translation speed (V_t); with R = 40 km, V_t = 6 m s^{-1}, and U_{max} = 60 m s^{-1}, the model predicts a maximum H_s of 15.1 m. Hsu (*7*) suggested a simple empirically determined formula, $H_s = 0.2(P_R - P_0)$, where P_R = 1013 mbar is the pressure at the edge of the hurricane and P_0 = 935 mbar is the central pressure, resulting in an H_s of 15.6 m. Underestimation by these models likely stems from the absence of wave data under intense storms. Measurements of the extremely large waves directly under Ivan may act as a starting point for improving our understanding of the waves generated by the most powerful hurricanes.

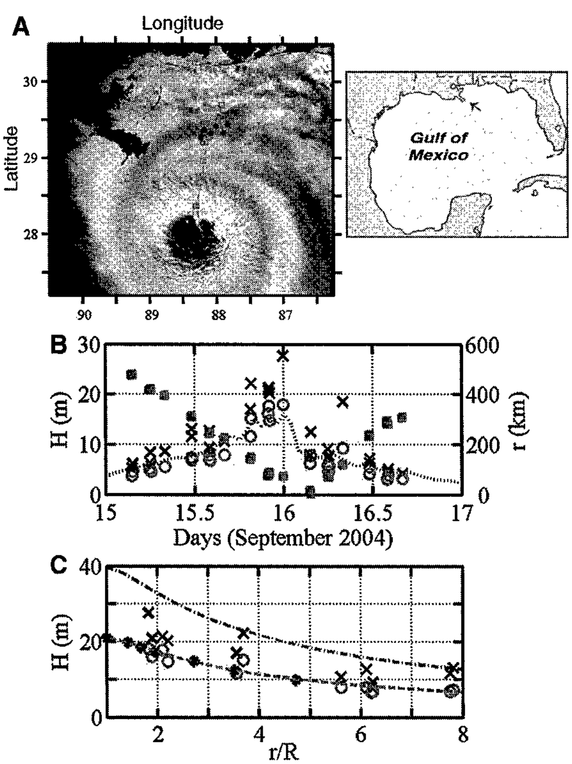

Fig. 1. (**A**) Satellite image of Hurricane Ivan from the Moderate Resolution Imaging Spectroradiometer (MODIS) at 1850 universal time, 15 September 2004 (provided by NRL's Ocean Optics Group). The eye of Hurricane Ivan is clearly shown just southeast of the boot of Louisiana. NRL moorings are shown as blue dots [northern line (60 m), moorings 1, 2, and 3; southern line (90 m), moorings 4, 5, and 6]. The NDBC buoy is shown as a red circle, and the track of Hurricane Ivan is shown as a green dashed line with squares marking the hurricane's center every 3 hours. (**Inset**) Location of Ivan at the time of measurement. (**B**) Time evolution of H_s (circles) and H_{max} (crosses) for the six NRL moorings, H_s for NDBC buoy 42040 (dotted line), and radial distance to Ivan's center (squares). (**C**) H_s and H_{max} as a function of normalized radial distance (r/R). The red dashed line represents the exponential relation (Eq. 1); digitized values of a segment 15° clockwise from the forward direction of a numerically simulated wave field are denoted by black asterisks. The blue dashed line represents $H_{max} = 1.9H_s$, and circles and crosses are as in (B).

References and Notes

1. Materials and methods are available as supporting material on *Science* Online.
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Fig. S1

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